The speed of quantum information and the preferred frame: analysis of experimental data

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Abstract

The results of EPR experiments performed in Geneva are analyzed in the frame of the cosmic microwave background radiation, generally considered as a good candidate for playing the role of preferred frame. We set a lower bound for the speed of quantum information in this frame at 1.5×10^4c.

1 Introduction

The tension between quantum mechanics (QM) and relativity manifests itself in two classes of theoretical problems. The first class of problems can be labelled "the search for a covariant description of the measurement process". Possibly the best-known example is the impossibility of a causal description of the collapse in an EPR experiment that would be valid in all frames; but there are many other examples, even for one-particle measurements, as widely discussed by Aharonov and Albert [1, 2]. The second class of problems is linked with some structural problems of quantum relativistic theories, like the definition of a position operator that fulfills "basic" requirements [3, 4, 5].

In this paper, we are concerned with the first of these classes. Actually, from an "orthodox" standpoint, these problems have been solved [1, 6, 7]: two observers, each using quantum prescriptions, predict the same final probabilities — recall that in its orthodox interpretation, QM deals only with probabilities, while the state vector and its evolution are not endowed with reality [8]. But several physicists are not satisfied with this solution, for different reasons [9]. For us, the tension between the notion of event that appears in relativity, and the reversible evolution of the quantum state, may be a guide for new physics.

The introduction of a preferred frame (PF) is a way out of the first class of problems, that would allow a realistic (obviously non-local) description of the quantum measurement [10]. Moreover, it seems that the PF would also be a way out of the second class of problems [3, 4]. To our knowledge, the introduction of a PF is still an intellectual tool (or trick): no experiments are planned or even proposed that aim to falsify this

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hypothesis [11]. An experiment can be easily conceived that falsifies a *joint hypothesis*: suppose that there is a PF *and* that in the PF the speed of quantum information is finite, though superluminal [12]. Then, if quasi-simultaneity in the PF is achieved in an EPR experiment, the EPR correlations should disappear.

In this paper we throw some light on this question by analysing long-distance EPR experiments performed between two telecom stations (Bellevue and Bernex) separated by 10.6 km [13]. The main idea is that, having observed standard EPR correlations, we are able to set a lower bound for the speed of quantum information [14] in any given frame. The structure of the paper is as follows. In Section 2, we define the speed of quantum information, and give its transformation law under a Lorentz boost. In Section 3, we introduce a good candidate for the PF, namely, the frame of the cosmic microwave background radiation (CMB), and give its speed with respect to the rest frame of our laboratory (G-frame, where G stands for Geneva). The results of these two sections are combined in Section 4 with experimental data, leading to the announced lower bound for the speed of quantum information in the CMB-frame. Section 5 is a conclusion.

2 The speed of quantum information

In an optical EPR experiment (figure 1), two photons are produced in an entangled state and sent to two analyzing stations A and B. The quantum entanglement manifests itself by the interference fringes that are observed in the coincidence counts of the detectors in A and B. These interferences are predicted by QM; still, many physicists are not at ease with correlations that arise between two space-like separated events. The correlation are sometimes considered as due to a "superluminal influence" that the first particle to reach its detector sends to the second one. In this work, we call "speed of quantum information" $\vec{v}_{QI}$ the superluminal speed at which this "influence" should propagate from one station to the other one. Of course, if two events are space-like separated, there is always a frame in which the two events are simultaneous ($v_{QI} = \infty$), and a family of frames in which the ordering of the arrivals is inversed with respect to the laboratory frame. Therefore the supposed "superluminal influence" is a real physical process only in a preferred-frame theory, or in a theory in which the meaningful frames are not arbitrary [15]. However, the operational definition of $\vec{v}_{QI}$ involves events (detections), that can be parametrized by using the standard relativistic formalism; in other words, a speed of quantum information can be defined formally in any frame. Its definition goes as follows: since correlations were observed, the quantum information must have travelled the distance between the two detectors in the time interval between the two detections. Let's define the x axis as the axis linking the detector in A and the detector in B, oriented from A to B. Therefore, if the event "detection at A" is parametrized in a given frame by (x_A, t_A), and similarly for the event "detection in B", the speed of quantum information must have the same direction as and have a higher value than

$$v_{QI,min} = \frac{x_A - x_B}{t_A - t_B} \,. \tag{1}$$

Let $\vec{v}$ be the speed of a given frame with respect to the laboratory frame, v_x its projection on the x axis. The Lorentz transform allows us to express $v_{QI,min}$ as a function of the values measured in the laboratory frame:

$$\left.\begin{array}{rcl} x & = & \gamma(x_{Lab} - v_x t_{Lab}) \\ t & = & \gamma(t_{Lab} - v_x x_{Lab}/c^2) \end{array}\right\} \;\rightarrow\; v_{QI,min}(v_x) \;=\; -\frac{d_{AB} + v_x\tau}{\tau + v_x d_{AB}/c^2} \tag{2}$$

where $\gamma = (1-v^2/c^2)^{-1/2}$, $d_{AB} = x_{B,Lab} - x_{A,Lab}$, which is positive by our convention, and $\tau = t_{A,Lab} - t_{B,Lab}$, which is positive if the detection at A occurs, in the laboratory frame, after the detection in B. Introducing the dimensionless parameters $\beta_x = v_x/c$, describing the boost, and $r = c\tau/d_{AB} = c/|v_{QI,min}(Lab)|$, describing the setup in the laboratory frame, we find the expression

$$v_{QI,min}(\beta) \;=\; -c\,\frac{1 + r\beta_x}{r + \beta_x}\,. \tag{3}$$

Thus $v_{QI,min}(\beta)$ depends on the orientation of the setup through β_x, and on the *relative* precision of the alignement r. It can be checked that $|v_{QI,min}(\beta)| > c$ if and only if $|v_{QI,min}(Lab)| > c$ ($r < 1$), independent on β; this is indeed a necessary property of the speed of quantum information, since two events that are space-like separated cannot be found to be time-like separated in any frame. From now on, we suppose that we consider space-like separated events ($r < 1$).

We conclude this section by noting that, due to finite accuracy in the experiments, one can never conclude to perfect simultaneity. In an EPR experiment, the localization $\Delta\tau$ of the photons is a limit to the accuracy; the best localization that can be achieved is the coherence length τ_c . The upper limit of $|v_{QI,min}(\beta)|$ that we can reach is thus d_{AB}/τ_c in all frames. The next section introduces a particular moving frame, the CMB-frame.

3 Linking the G-frame to the CMB-frame.

As emphasized explicitely in several works, even recently [4, 9, 10], the frame of the cosmic microwave background radiation (CMB-frame) is a natural candidate for playing the role of PF. The CMB-frame is defined as the frame in which the cosmic background radiation is isotropic [16].

To find the relative speed of the G-frame with respect to the CMB-frame, we need to take into account: (i) The speed $\vec{v}_{S)CMB}$ of the barycenter of the solar system (identified with the Sun for our purposes) with respect to the CMB; (ii) the speed of the Earth with respect to the Sun $\vec{v}_{E)S}$, and (iii) the spin of the Earth, giving the speed of Geneva with respect to the center of mass of the Earth $\vec{v}_{G)E}$. The speed $\vec{v}_{S)CMB}$ is given in the literature [17]: its magnitude is $v_{S)CMB} = 371$ km/s; its direction in the orthogonal celestial coordinates (see fig. 2) is ($\alpha = 11.20^h, \delta = -7.22°$). For the other two speeds, we have in magnitude: $v_{E)S} = 2\pi D_{\oplus}/(1\,year) \approx 30$ km/s, where $D_{\oplus}$ is the distance Earth-Sun; and $v_{G)E} = 2\pi R_{\oplus}\cos l_G/(24\,hours) \approx 0.31$ km/s, where $R_{\oplus}$ is the Earth's radius and $l_G \approx 43°$ is the latitude of Geneva. The three speeds being much smaller than c, we can use the Galilean addition rule:

$$\vec{v}_{G)CMB} \;=\; \vec{v}_{G)E} + \vec{v}_{E)S} + \vec{v}_{S)CMB}\,. \tag{4}$$

Due to its magnitude, the correction $\vec{v}_{G)E}$ can be neglected in numerical estimates. Of course, the speed of the CMB-frame with respect to the G-frame is given by $\vec{v}_{CMB)G} = -\vec{v}_{G)CMB}$.

To go further, we need to introduce a system of coordinates, which can be chosen arbitarily. We choose a cartesian coordinate system defined as follows: the z-axis is the North-South axis of the Earth, oriented in the N direction. The celestial equatorial plane is therefore the (x, y) plane. In this plane, the x direction is chosen to be the direction of the vernal point, that is the point where the eclyptic intersects the celestial equatorial plane at the Spring equinoxe (see fig. 2). Thus:

$$\vec{v}_{S)CMB} = v_{S)CMB} \begin{pmatrix} \cos\phi_v \, \sin\theta_v \\ \sin\phi_v \, \sin\theta_v \\ \cos\theta_v \end{pmatrix} \tag{5}$$

with $\phi_v = 11.20h = 168°$ and $\theta_v = 97.22°$ [17]. Also, neglecting the excentricity of the Earth's orbit, it is not difficult to show that

$$\vec{v}_{E)S} = \omega_y \, D_\oplus \begin{pmatrix} -\sin(\omega_y t + \theta_0) \\ \cos(\omega_y t + \theta_0) \, \cos\theta_e \\ -\cos(\omega_y t + \theta_0) \, \sin\theta_e \end{pmatrix} \tag{6}$$

where $\omega_y = \frac{2\pi}{1\,year}$ and $\theta_e = 23,5°$ is the inclination of the eclyptic plane with respect to the equatorial plane. We still have to define the origin of time. It is natural to set $t = 0$ at the beginning of the EPR experiment we want to analyse. Since the acquisition time is typically some hours, $\omega_y t$ in (6) can be set to 0. The definition of $t = 0$ provides also the interpretation of θ_0: this angle is defined as $\omega_y \Delta T$, with ΔT the time elapsed since the Spring equinoxe at the moment of the experiment.

Recall that in eq. (3) we must enter the projection of $\vec{v}_{CMB)G}$ on the direction defined by the straight line joining the two detectors. In our coordinate system, this direction is given by

$$\hat{e}_x \equiv \frac{\vec{AB}}{|\vec{AB}|} = \frac{1}{N} \begin{pmatrix} \sin\theta_B \cos\phi_B - \sin\theta_A \cos\phi_A \\ \sin\theta_B \sin\phi_B - \sin\theta_A \sin\phi_A \\ \cos\theta_B - \cos\theta_A \end{pmatrix} . \tag{7}$$

where $N = \sqrt{2}[1 - \cos\theta_A \cos\theta_B - \sin\theta_A \sin\theta_B \cos(\phi_A - \phi_B)]^{1/2}$. If A is Bellevue (46°15′N, 6°09′E) and B is Bernex (46°10′N, 6°05′E), then we have: $\theta_A = 43°45'$, $\theta_B = 43°50'$, $\phi_A = \phi_0 + \omega_d t$, $\phi_B = \phi_0 + \omega_d t - 0°04'$. The angle ϕ_0 measures the position of the vernal point with respect to the meridian of Bellevue at the beginning of the experiment.

4 Analysis of experimental data

For the study of the speed of quantum information with an EPR setup, the precision of the alignment $|r| = c\tau/d_{AB}$ is the figure of merit. In fact, looking at eq. (3), we see that the simultaneity condition $r + \beta_x = 0$ can be satisfied only if the precision of the alignment r satisfies $|r| < \max_t|\beta_x(t)| \approx |\vec{v}|/c$. Thus, the smaller the speed of the considered frame with respect to the laboratory frame, the higher the precision required to satisfy the simultaneity condition. In other words, for a given frame, two situations may arise: (i) The situation of *bad alignment* is described by $|r| > \max|\beta_x|$. In this case, $|v_{QI,min}(\beta)| \approx \frac{c}{|r|}$. (ii) The situation of *good alignment* is the opposite one: the simultaneity condition can be satisfied. $|v_{QI,min}(CMB)|$

is no more limited by r, but there are still two possible limiting factors. The first one is the localization of the photons, that we have already mentioned. To discuss the second one, we begin by noting that β_x varies with time due to the rotation of the Earth around its axis, since the line Bellevue-Bernex is not parallel to this axis — and in fact, $\hat{e}_x$ given by eq. (7) varies with t through ϕ_A and ϕ_B. In particular, β_x is not constant during the time needed to record an interference fringe. The speed $v_{QI,min}(\beta)$ depends on β_x and on r, so in principle one could keep it constant even though β_x changes, "simply" by performing the suitable continuous correction of the alignment r. In practice, such a protocol is cumbersome. So $v_{QI,min}(\beta)$ also varies during the recording of a fringe. This second limiting factor is actually the most important one, as will be shortly shown.

If the considered frame is the CMB-frame, whose motion is rather slow since $|\vec{v}_{CMB)G}| \approx 300$ km/s, then a good alignment is obtained for $|r| \sim 10^{-3}$. Since such a precision was not looked for, the alignment was probably "bad" in most of the previously reported EPR experiments [18]. In the experiment that we are going to consider [13], the distance between the detectors was 10.6 km, and the difference in the two arms was lowered down to 1-10 mm, whence $|r| \geq 10^{-6}$: the "good alignment" criterion for the CMB-frame is clearly fulfilled. Due to chromatic dispersion in the fibers, the localization of the photons was $\Delta\tau = 90$ ps, so that the maximal value of $|v_{QI,min}(CMB)|$ that we can hope to obtain is about $3.5 \times 10^5\, c$ [19]. It took about one hour to record a fringe, the detection rates being lowered by the photon losses in the fibers.

A typical EPR correlation trace is given in fig. 3 (a). This data acquisition started on June 1st 1999 at 15h30 UTC (whence $\theta_0 = 1.24$ rad and $\phi_0 = 2.247$ rad), and ended on June 2nd at 6h30 UTC. Slight variations of the temperature led to a variation of the length of the fibers linking the source to the analyzing stations, that is, to a variation of the alignment τ in the G-frame. We did not monitor $\tau(t)$ continuously; we assume a linear interpolation between the initial value $c\tau_i = 2$ mm, and the final value $c\tau_f = 14$ mm. This assumption completes the set of numerical values needed to evaluate $|v_{QI,min}(CMB)|$ according to formula (3), as a function of time, that is, as a function the Earth's rotation around its axis. The numerical evaluation is shown in fig. 3 (b). We see that at a given moment (about 3h UTC) the detection events were simultaneous in the CMB-frame. Even at that moment, the visibility of the fringes is not reduced. By requiring the reduction of a whole half-fringe as a conservative criterion for fixing a limit to the speed of quantum information, we find the lower bound $|v_{QI,min}(CMB)| = 1.5 \times 10^4\, c$.

5 Conclusions

We have presented the first analysis of the results of an EPR experiment in the frame of the cosmic microwave background radiation. The conservative bound that we obtained for the "speed of quantum information" in that frame, $|v_{QI,min}(CMB)| = 1.5 \times 10^4\, c$, is still quite impressive, but, like most physicists, the present authors will not be astonished if further experiments provide an even higher value. The method of analysis that has been developed in this work could of course be applied to all possible frames [20].

In the experiment that we analyzed, the recording of the fringes is slow compared to the variation of v_x induced by the rotation of the Earth, and this is the constraint that fixes the above limit of $|v_{QI,min}(CMB)|$.

The precision required for some planned experiments with laboratory distances [21] should increase the bound $|v_{QI,min}(CMB)|$ up to $5 \times 10^5\, c$, the rotation of the Earth still being the most important limiting factor. As an order of magnitude, we estimated that a fringe should be completed in less than 5 seconds in order to reach the limit imposed by the localization of the photons.

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[11] Obviously, we don't discuss here historical versions of the PF (the "ether" of the XIX century), for which experiments have been designed and performed. The requirement, that a PF for quantum phenomena must not predict wrong results for classical experiments, can be fulfilled [3, 4].

[12] Ph. Eberhard, *A Realistic Model for Quantum Theory with a Locality Property*, in: W. Schommers (ed.), *Quantum Theory and Pictures of Reality* (Springer, Berlin, 1989)

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[14] We call "speed of quantum information" what is probably better known as "speed of the spooky-action-at-a-distance", in Einstein's terms.

[15] A. Suarez, V. Scarani, *Phys. Lett. A* **232** (1997) 9-14

[16] All the basic definitions and an up-to-date review of the experimental data about the CMB can be found online at this URL: http://pdg.lbl.gov.

[17] C. Lineweaver *et al.*, *Astrophys. J.* **470** (1996) 38-42.

[18] As expected, a discussion of the precision of the alignement is missing in most works, because this was not a primary concern in EPR experiments. The Innsbruck group reported a precision of 1/500 for their experiment on 500m [G. Weihs *et al.*, *Phys. Rev. Lett.* **81** (1998) 5039-5043]. For experiments in a laboratory like Aspect's [A. Aspect *et al. Phys. Rev. Lett.* **49** (1982) 91-94], "good alignement" would mean that the two arms of the interferometer should differ by at most 10mm.

[19] In some experiments described in [13], a filter was used to reduce the effect of the chromatic dispersion, leading to $\Delta\tau = 5$ ps. We thus obtained in the G-frame $|v_{QI,min}(Lab)| \approx \frac{2}{3}10^7\,c$. For our present analysis we don't need such a precision, since the spin of the Earth is the most important limiting factor.

[20] Due to the precision $r \geq 10^{-6}$, the experiment presented above satisfies "good alignement" for all frames moving at speed of more than ~ 3 km/s with respect to the G-frame.

[21] A. Suarez, *Phys. Lett. A* **269** (2000) 293

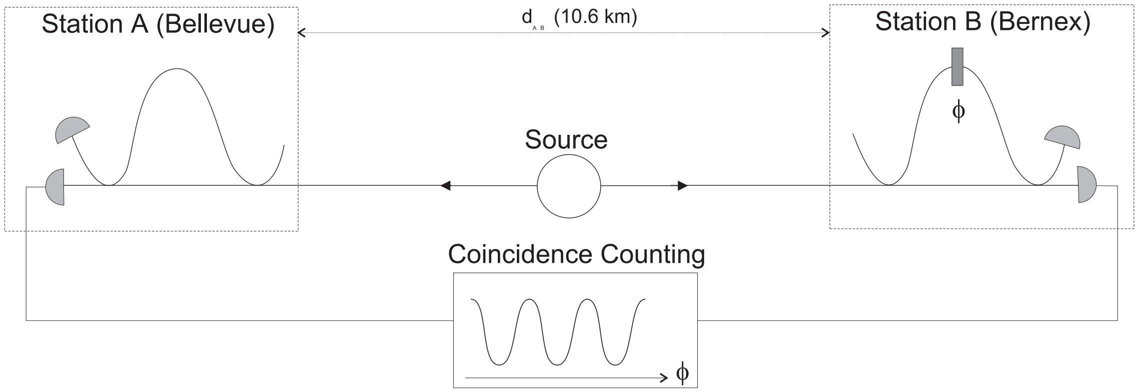

Figure 1: Schematic of the experiment consisting on a photon pair source and two analyzers separated by more than 10 km.

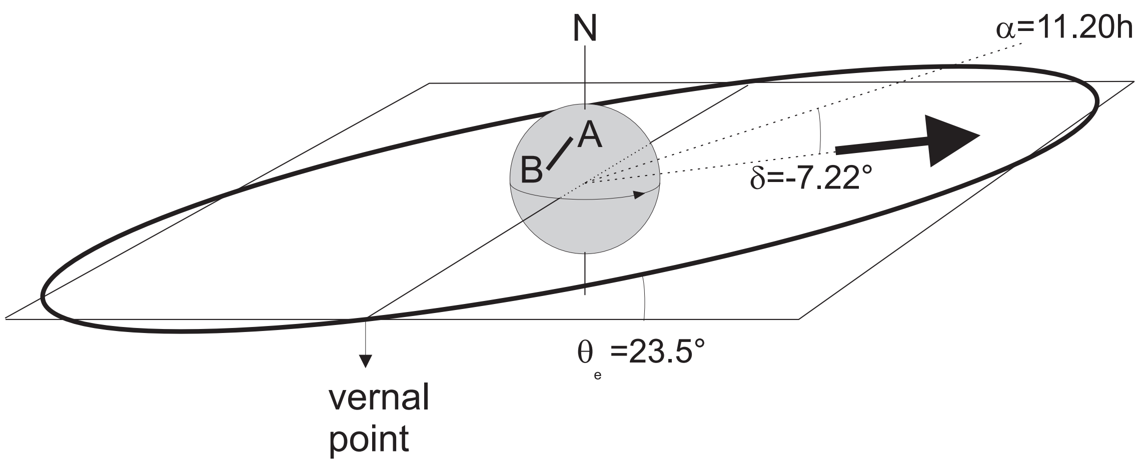

Figure 2: Schematic representation of the direction of $\vec{v}_{S)CMB}$ (black arrow). The sphere is the Earth, A is Bellevue and B is Bernex. The plane (celestial equator) contains the equator of the Earth; the black curve is the trajectory of the Sun as seen from the Earth (eclyptic). The vernal point is defined as the intersection of the celestial equator and the eclyptic at the Spring equinoxe.

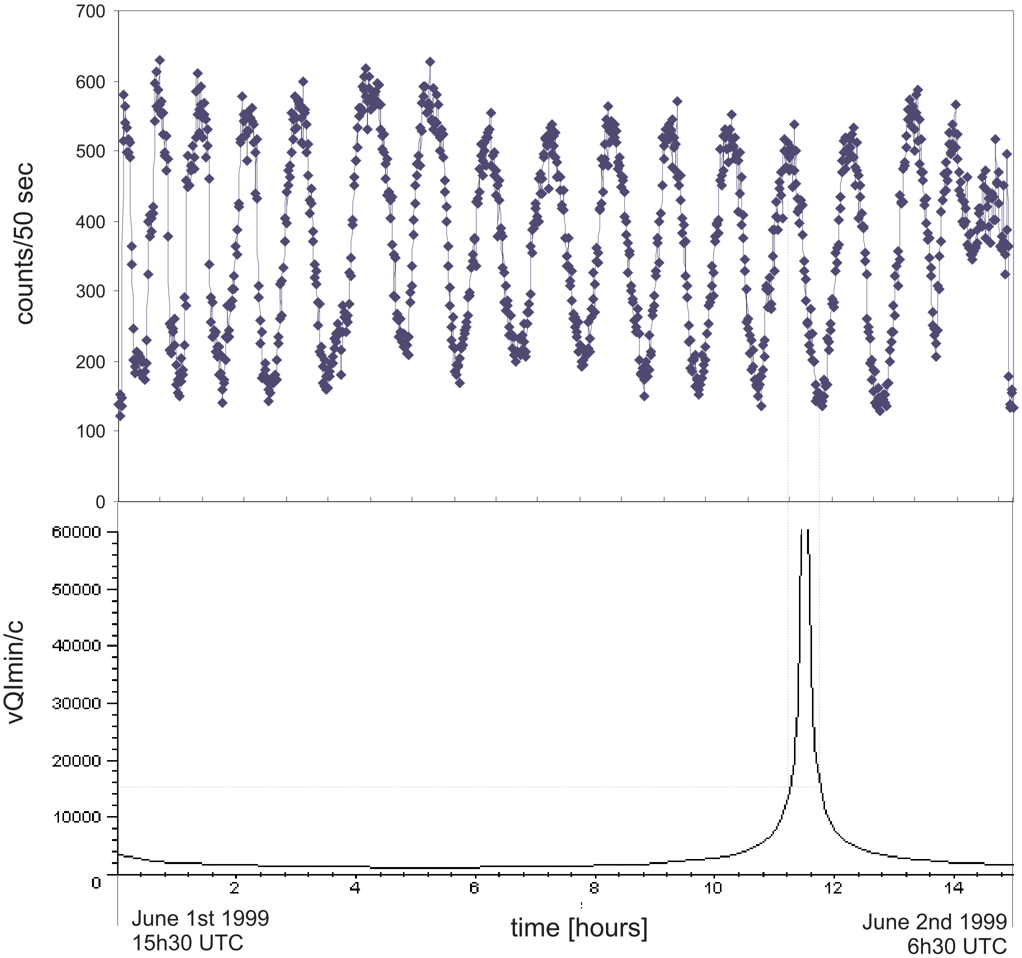

Figure 3: (a) Two-photon interference fringes measured over 15 hours, each data point corresponds to a time interval of 50 s. (b) The value of $|V_{QI,min}(CMB)|$ calculated by eq. (3) for the day and hours of the experiment.